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Normalising domestic space heating demand using *post hoc* models

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Abstract

Current evidence suggests that the energy performance gap (EPG) between predicted and actual use of energy in buildings is significantly weighted towards under prediction and can be as high as 200%. High quality modelled and actual data are needed to ensure like for like comparisons (LFLC) when investigating the EPG. Internal temperature (t_i) normalisation is a key process to ensure LFLC but is often hampered by the lack of the original model due to the time lag between design, construction and occupancy.

Here, we demonstrate the use of models created after data collection – i.e. *post hoc* – as a substitute for original models in evaluating the EPG. The robustness of the internal temperature normalisation factor (f_{ti}) is tested using measured data from 20 Passivhaus homes. The data from each home is inputted into 10 PHPP and 10 SAP models with highly different domestic and non-domestic building configurations, creating 400 model variants. Each variant is further split into 4 cases of varying internal gains and solar radiation creating a total of 1,600 variants. Results demonstrate that f_{ti} is resilient to differences in building configuration, solar radiation levels and varying internal gains (SEM <0.02). Even though SEM increases when measured internal temperatures are below base assumptions, the impact of this error on the computed space heating demand is at most 4%. This suggests that *post hoc* models can be a substitute for actual models in evaluating the energy performance gap and that limited site data can still yield robust results.

Keywords
Passive House Planning Package, PHPP, SAP, space heating demand, normalisation, internal temperature, building modelling, performance gap.

Practical Application
Identifying the causes of the energy performance gap (the difference between modelled and measure energy demand) is complex. Normalising space heating demand for internal temperatures means that some differences between modelled and actual space heating demand can be accounted for. Building models such as Passive House Planning Package (PHPP) and SAP are readily available and allow variations in climate and temperature data to be inputted. This research demonstrates that in practice any PHPP and SAP model can be used for normalisation, not just one that is building specific and that some parameters (internal temperature) are more important than others. This provides a simple and easily accessible approach to temperature normalisation that can be applied by industry to domestic dwellings.

1. Introduction

The energy performance gap in buildings is the difference between the predicted performance from building modelling and the actual measured energy used once the building is occupied [1-4]. The reasons reported for the performance gap are wide ranging and include aleatory as well as epistemic errors induced via modelling, construction [3, 5-9], and user behaviour [10-12].

A basic first step is to ensure a like-for-like comparison between the building model and the building as it performs in use. It would hardly be surprising to find differences between modelled and actual energy performance if, for example, the model assumed different indoor temperatures than those observed. Indeed, it is well-known that the difference between indoor and outdoor temperatures (ΔT) strongly influences space heating demand [13-16] and each 1°C increase in internal temperature translates to a 10% increase in space heating in typical models. In many steady-state models, which are the most commonly used for domestic scale buildings, ΔT is used as the basis for calculating heating and cooling degree days[1] [17], which are then used in the modelling to estimate heat losses and heating demand [18].

Steady-state building simulation models such as Passive House Planning Package (PHPP) and the UK's Standard Assessment Procedure (SAP)[2] assume monthly fixed internal temperatures and regional climate data to generate degree days [19, 20]. In reality, annual weather patterns will be different and site-specific weather may vary from that collected at a regional weather station, which may be some distance from the site. These differences in external temperatures (T_e) could result in higher or lower heating demand than predicted during modelling [21]. In addition, occupants may heat their homes to higher than assumed internal temperatures (T_i) or for longer, for comfort reasons [22, 23], which will result in different degree day calculations. Other factors such as elevation and solar radiation can also result in inaccuracy of average weather data for a specific site, and therefore under or over estimates of heating demand [14]. Since each of these is essentially an input to the model, any differences arising between model outputs and observed data should be isolated from differences in model inputs. This is the standard process of normalization.

George Box's well-known aphorism that 'All models are wrong, but some are useful' [24] suggests that when examining the performance gap, the goal must be to assess whether a given model is a 'good enough' representation of a building's performance *provided the model inputs are a 'good enough' representation of reality*. This is obviously complicated when the original model used to construct the building is itself unavailable. Hence, the goal of this paper is to ask whether a model created after a building is constructed – i.e. *post hoc* – is suitable for use in energy studies. In particular, we wish to examine how sensitive the temperature normalisation procedure is to differences in other model inputs, which could be a major source of uncertainty in the creation of *post hoc* models.

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[1] Using either a 'base' temperature or the internal temperature.
[2] It is noteworthy that although SAP was developed as a compliance tool and not a tool for predicting energy use, it is widely used as such due to its ease of use and inheritance from the more robust BREDEM class of models.

1.1. Temperature Normalisation Methods and Degree Days

Temperature normalisation allows for an adjustment for differences in measured internal and external temperatures compared to model assumptions. Without normalisation, inferences could be made about the gap between modelled estimates and measured space heating demand (energy performance gap), which could be accounted for by the differences between modelled, and actual, internal and external temperatures. There are several approaches to temperature normalisation, as discussed below.

CIBSE TM41 describes a simple method where weather related heating loads are divided by local annual degree days and multiplied by the UK 20-year average degree days (usually 2462K Day based on a 15.5°C base internal and external temperature) to allow the comparison of buildings from different regions [17].

$$Q_{H(normalised)} = \left(\frac{Q_{H(measured)}}{Local\ Annual\ Degree\ days}\right) * UK20\ average\ annual\ degree\ day\ value$$

(Equation 1)

A variation on this approach calculates the ratio between actual heating degree days and average heating degree days, this ratio is then applied to space heating demand to normalise [25].

$$Q_{H(normalised)} \left(\frac{Average\ annual\ degree\ days}{local\ annual\ degree\ days}\right) * measured\ space\ heating\ demand$$

(Equation 2)

However, these approaches are based on fixed internal temperature assumptions, which in the UK is usually a base temperature of 15.5°C plus an assumption for internal gains, giving a total of 18.3°C, and only considers variations in external temperatures. More accurate normalisation methods should take into account site specific base temperatures, as using the standard technique described above, will produce incorrect results for buildings with lower or higher base temperatures [17]. Other factors such as solar radiation and internal gains will also affect space heating demand, and these are not included in the CIBSE method.

Berggren and Wall [26] describe two methods for energy normalisation:

1) A static method includes correcting for variations in internal temperatures using the assumption of a percentage increase or decrease in space heating demand based on deviation of internal temperatures from the modelling assumptions. Here heating is adjusted by 5% for each degree difference between modelled and measured internal temperatures.

$$Correction\ factor\ (cf) = (1 + (T_{modelled} - T_{measured}) * 0.05)$$

(Equation 3)

2) A dynamic method calculates the ratio of energy demand from the building model under normal conditions, with an updated model with actual building use and external temperatures.

Both these approaches consider internal temperatures and are therefore an improvement on TM 41.

The EU-funded CEPHEUS research project [27], developed a normalisation methodology to adjust for fluctuating internal temperatures, taking into account measured external temperature and solar radiation. This method of normalisation allows for location and time specific weather data (external temperature and solar radiation) to be used and for monthly variations in internal temperatures to be accounted for, using the project specific PHPP assessment sheets. It is a variation of the one proposed by CIBSE in TM 41 where the ratio of average heating degree days and actual heating degree days is calculated and is an improvement as solar radiation is also taken into account, and is similar to the dynamic method described by Berggren, but using steady state simulation software [17, 26]. Hence, we take the CEPHEUS method as the current state of the art for normalisation in steady state simulation.

The method of calculation is given in below.

Table 1. Summary of normalisation method from CEPHEUS (2003). The 'climate' and 'verification' sheets refer to those sheets in PHPP that contain the external weather data and input / output data, respectively. These are standard names though minor variations exist between versions.

Step	**Variable to compute**	**Explanation**
Step 1	$Q\ Heating_{measured}$	Measured annual space heating demand [kWh] the real dwelling.
Step 2	$Q\ Heating_{20}$	Annual space heating demand [kWh] summed from monthly values in PHPP using measured monthly external temperatures and solar radiation manually inputted into the 'climate' sheet. Use the standard internal temperature of 20˚C in the 'verification' sheet. Sum monthly heating demand to calculate $Q\ Heating_{20}$.
Step 3	$Q\ Heating\ _{real}$	Same as $Q\ Heating_{20}$ but with measured monthly internal temperatures, manually inputted into the 'verification' sheet.
Step 4	Calculate normalisation factor (f_{ti})	$f_{ti} = \frac{Q\ Heating_{20}}{Q\ Heating_{real}}$
Step 5	Apply normalisation factor to measured space heating	$Q\ Heating_{norm} = QHeating_{measured} * f_{ti}$

1.2. Building modelling tools

In this paper, we consider two steady-state building energy modelling tools widely used in the UK:

1. Passive House Planning Package (PHPP): PHPP is a building energy calculation tool developed by the Passive House Institute in Germany. It is used to design to and demonstrate compliance with, the Passivhaus Standard and was first published in 1998. Since then, there have been several revisions and the current version (V9) allows the tool to show compliance with near zero energy buildings (NZEBs) in line with the EU Energy Performance in Buildings Directive (EPBD). PHPP uses the principles of BS EN ISO 13790 with additional algorithms to calculate both space heating demand and heating loads [20, 28].

2. Standard Assessment Procedure (SAP): SAP is the UK Government's methodology for measuring the energy performance of dwellings and for calculating Energy Performance Certificates (EPCs). SAP is based on the Building Research Establishment (BRE) Domestic Energy Model (BREDEM) and is compliant with BS EN ISO 13790 [29]. The main outputs of SAP (2012) are the SAP rating, Dwelling Emission Rate (DER) and Fabric Energy Efficiency (FEE), which are used to show compliance with Approved Document Part L1A of Building Regulations. All new domestic dwellings in the UK will be subject to a SAP assessment. The current version is SAP (2012).

The shared philosophy and general compliance with BS EN ISO 13790 allows us to compare results from both tools. However, differences in implementation necessitate a careful consideration of the parameters involved in the temperature normalisation process. These are discussed further below, specifically with respect to PHPP (v9) and SAP (2012).

Space heating demand calculations

PHPP (v9) and SAP (2012) calculate monthly space heating demand following EN 13790:2008. This calculation is based on fixed and constant monthly internal and external boundary conditions [30]. Within PHPP (v9) it is possible to change average monthly external temperatures and solar radiation in the 'climate' sheet and internal set temperature in the 'verification' sheet. In SAP (2012) these conditions can be changed within an excel spreadsheet version of the SAP (2012) worksheet.

The formula to calculate the space heating demand (Q_H) is the energy balance between heat losses through the building fabric (transmission losses Q_T) and ventilation losses (Q_V) and heat gains (solar (Q_S) and internal or incidental gains (Q_I)) and is shown in Equation 4.

$$Q_H = \big((Q_T + Q_V) - (Q_S + Q_I)\big)$$

(Equation 4)

In addition, both PHPP and SAP (2012) calculate a utilisation factor (η_H) which relates to how much internal gains can be usefully employed in a dwelling [20, 29]. Using this equation, PHPP will calculate the gains and losses and if this difference is greater than 0.1kWh then the period under consideration will be included in the calculation of Q_H.

[31]. SAP (2012) excludes any heating demand in the summer months (June, July, August) in the space heating demand calculation [29].

Even in a well-insulated dwelling such as a Passivhaus, the heat losses through the opaque elements will be the largest element of the heat loss calculation [31]. PHPP calculates transmission heat losses from the measured area (m²), U value ($Wm^{-2}K^{-1}$), reduction factor and heating degree hours measured in kilo-Kelvin hours per year ($kKha^{-1}$). Heating degree hours are shown as G_t. Essentially, a heating degree hour (G_t) is the length of time (h) a degree of heating (K) is required. The number of hours will depend on the external temperature and internal temperature [28]. G_t is calculated from the following

$$G_t = \left((T_i - T_e)\, x \frac{t}{1000} \right)$$

(Equation 5)
Where,
t is the length of time under review in hours (h)
T_i is internal temperature (generally fixed at 20ºC)
T_e is average monthly external temperature (ºC)

Figure 1gives a sample calculation from PHPP (v9) showing the calculation of transmission losses using these values.

(This page displays the sums of the monthly method over the heating period)

Climate: South East England — Interior temperature: 20 °C
Building: Wishanger EcoHouse — Building type/use: detached
Location: Headley — Treated floor area A_{TFA}: 545.9 m²
Spec. capacity: 204 Wh/(m²K) (Enter in "Summer" worksheet.)

	Building element	Temperature zone	Area m²		U-value W/(m²K)		Month. red. fac.		G_t kKh/a		kWh/a	per m² Treated Floor Area
1.	Exterior Wall - Ambient	A	417.9	*	0.182	*	1.00	*	71	=	5368	
2.	Exterior Wall - Ground	B		*		*	1.00	*		=		
3.	Roof/Ceiling - Ambient	A	625.5	*	0.104	*	1.00	*	71	=	4569	
4.	Foor slab/ basement ceiling	B	633.0	*	0.102	*	1.00	*	45	=	2879	
5.		A		*		*	1.00	*		=		
6.		A		*		*	1.00	*		=		
7.		X		*		*	0.75	*		=		
8.	Windows	A	109.6	*	0.838	*	1.00	*	71	=	6477	
9.	Exterior Door	A	8.4	*	0.789	*	1.00	*	71	=	468	
10.	Exterior TB (length/m)	A	493.0	*	0.035	*	1.00	*	71	=	1232	
11.	Perimeter TB (length/m)	P	122.0	*	0.040	*	1.00	*	45	=	218	
12.	Ground TB (length/m)	B		*		*	1.00	*		=		
	Transmission Heat Losses Q_T									Total	21211	38.9 kWh/(m²a)

Figure 1. Sample transmission loss calculation for a single domestic dwelling (monthly method sheet PHPPv9).

SAP (2012) uses a similar calculation methodology to PHPP. Space heating demand is the balance between heat losses through the building fabric and ventilation and solar and incidental gains. SAP (2012) calculates the heat loss rate (L_m) in Watts for both building fabric and ventilation using Equation 6.

$$L_m = h_c(T_i - T_e)$$

(Equation 6)
Where,
h_c is the heat transfer coefficient taken as sum of fabric and ventilation losses ($W/m^{-1}K$)
T_i is mean internal temperature (see below) (ºC)
T_e is average monthly external temperature (ºC)

Internal temperatures and climate data

For a domestic dwelling unless there is a justified case, in PHPP (v9) the internal temperature will be set at 20ºC. In SAP (2012), internal temperatures within the model are based on two zones and there are separate calculations for the living area and the rest of the dwelling. It is assumed that the living area is heated to 21ºC and the rest of the dwelling to a lower temperature based on heating controls and the heat loss parameter (HLP) calculation. Therefore, less energy efficient homes (with higher HLP) will be modelled on lower internal temperature assumptions and more highly efficient homes will be modelled on internal temperature assumptions more in line with PHPP (v9). The calculation method for mean internal temperatures can be found in Table 9 in the SAP (2012) guidance [29].

An internal temperature of 20ºC is in line with mean measured internal temperatures in new and existing dwellings within the UK [13, 23, 32]. However, actual temperatures from which this mean is derived range from 16ºC to 23ºC [13, 23]. Post occupancy evaluation (POE) of Passivhaus dwellings shows an average winter indoor temperature of 21.1ºC ranging between 20ºC and 24ºC [22, 33]. This difference between a population mean and the actual sample reflects the variation in indoor temperatures and should be considered when undertaking temperature normalization.

In PHPP (v9) monthly average external temperatures are taken from the 'Climate' sheet. Climate data can be obtained from embedded PHPP files, from software such as Meteonorm or from user inputted data. Within PHPP there are currently 22 embedded climate zones for the UK which correspond to the BRE weather regions used within SAP (2012). Regional weather files are only used in SAP (2012) for some calculations, and for space heating loads rather than using regional weather, SAP (2012) currently uses a UK average weather file based on regional data from the East Pennines.

Heat gains

Heat gains are calculated from solar and internal sources and in well insulated homes, internal and solar gains can contribute a significant proportion of the heat balance within a dwelling [34].

Solar gains in PHPP (v9) and SAP (2012) (Q_S) is calculated using the elements in Equation 7.

$$Q_S = r \cdot g \cdot A_W \cdot G$$

(Equation 7)
Where,
r is the reduction factor which includes the frame to window ratio, shading, dirt, and angle of inclination
g is the solar energy transmission coefficient for the glazing or g-value for the window
A_W is the rough window opening area (m^2) and
G is the total solar radiation in the heating period ($kWhm^{-2}a^{-1)}$)

Changes in solar radiation will vary the incidence of gains through both opaque and transparent building elements. The relationship between high solar radiation and space heating demand is not clear, especially in homes with triple glazing where solar energy transmittance g-values will be lower compared to single and double glazing [35]. Some research shows that high levels of solar radiation do not always translate into high levels of solar gain and external temperature is a more dominant factor in the estimation of heating (and cooling demand) [36], or that high radiation can mean higher space heating, as clear skies lead to cooler nights [37]. Other studies show that solar gains through triple glazing can be significant in winter if glazing areas are large [35].

Internal heat gains (IHG) account for heat generated from cooking, dishwashing, laundry, lights, consumer electronics, hot water distribution and metabolic gains from occupants [38]. For a Passivhaus dwelling, internal gains were generally fixed at 2.1 Wm^{-2}. The method for calculating internal gains has been amended in the new update of PHPP (v9) to better reflect the gains in smaller house sizes and higher electrical loads. Internal gains are now on a sliding scale from a maximum of 4.1Wm^{-2} for very small dwellings (≤25^2 TFA) to a minimum of 2.1 Wm^{-2} for dwellings with TFA ≥ 300m^2 [39]. An example of the change in IHG calculation in PHPP (v9) is given in Table 2.

TFA (m^2)	**Original IHG in PHPP v8 (Wm^{-2})**	**IHG calculated in PHPP v9 (Wm^{-2})**
40	2.1	3.4
65	2.1	2.9
90	2.1	2.7
120	2.1	2.5

Table 2. Change in internal heat gains (IHG) based on TFA using PHPP (v9).

Increasing internal gains for smaller buildings will reduce space heating demand, as more heat gains are attributed to IHG in the energy balance. For the UK, where homes tend to be smaller this change will facilitate meeting the Passivhaus standard.

Revisions in SAP (2012) have also addressed internal gains calculations. Earlier versions of SAP (2012) assumed much higher internal gains and occupancy rates compared to PHPP (v9). For less energy efficient homes these differences had a smaller influence, but in energy efficient homes such as Passivhaus or other low energy designs, internal gains assumptions could account for more than half the heat gains, this difference will impact on the space heating demand calculation [40]. Rather than using a fixed amount based on floor area, separate calculations, often based on assumed occupancy levels (which are linked to floor area), are made for metabolic, lighting, appliances, cooking, pumps and fans and water heating gains set against evaporation losses. Even so, in SAP (2012) the revised internal gains assumptions are still higher than PHPP (v9).
The influence of occupancy levels, internal temperatures and appliance use in both Passivhaus and highly insulated homes has been demonstrated using dynamic modelling and it was found that internal temperature, airflow behaviour and appliance use were significant factors and occupancy levels less so [41, 42].

Other differences

SAP (2012) and PHPP(v9) both calculate space heating requirement based on EN 13790. Steady state fabric and ventilation heat losses are calculated, with solar and internal gains subtracted, and degree days applied, but there are differences between the two models which are summarized in Table 3. These differences were more marked in previous versions but have been reduced with the revisions in SAP (2012) and PHPP (v9) [40, 43-45].

	SAP (2102)	PHPP (v9)
Dimensions	Internal measurements	External measurements
Internal floor area for energy and carbon calculations	Gross internal area	Treated floor area typically 10% less than gross internal floor area
Solar gains	Based on standard window sizes, shading measured in less detail	More detailed – each window is separately modelled for solar gain and shading
Internal gains	Standard assumptions and can be 100% higher than PHPP	Assumes best practice in choice of lighting and appliances
Ventilation and infiltration	Based on air permeability rates	Based on air change rates
Internal temperature	Living room fixed at 21°C, rest of the dwelling varies with efficiency of building fabric.	Fixed at 20°C
External temperature	Average UK data	Location and altitude specific

Table 3. Differences between SAP (2012) and PHPP (v9). Space heating calculation.

The impact of these differences has been researched and despite the models producing different outputs for heat losses and gains, when space heating demand alone was calculated these differences were less marked: SAP (2012) overestimated space heating by 2.8 kWh/m^2 compared to PHPP (v9) assessments for the same buildings [44]. Therefore, whilst there are differences between PHPP and SAP, there are sufficient similarities in the way that space heating demand is modelled. Hence, both building models can be used to test the calculation of a normalisation factor and allow for comparison.

2. Method

Since the CEPHEUS method represents the current state of the art for temperature normalisation, we use it as the starting point for our investigation. Our primary hypothesis is that building form and size have no significant impact on the accuracy of the calculation of the normalisation factor (f_{ti}) and therefore access to the site specific PHPP or SAP assessment is not critical. If true, this would simplify the normalisation process and be useful in improving post occupancy evaluations, as this adjustment could be made when the site specific PHPP or SAP sheet may not be available for commercial or other reasons.

In addition, we test the impact of varying internal and solar gains on the normalisation, given that these could have a significant effect on space heating demand, in highly-insulated dwellings such as Passivhaus.

The chosen methodology for testing our main hypothesis was:

A. Collect post occupancy data on internal and external temperatures, solar radiation and space heating demand from 20 certified Passivhaus dwellings. Twenty dwellings were deemed sufficient for this analysis provided they were reasonably inhomogenous (i.e. not of only one or two types / sizes).
B. Create *10 post hoc* models in PHPP covering a wide range of building typologies, treated floor areas and designs.
C. Input data from each building in Step A into every building model in Step B, varying internal and external temperatures following the CEPHEUS method (see Table 1).
D. Split each model in Step C into four Cases (See Table 5):
    Case 1. Solar gains per model default, internal gains fixed.
    Case 2. Solar gains per model default, internal gains varied using PHPP (v9).
    Case 3. Locally collected solar gains, internal gains fixed.
    Case 4. Locally collected solar gains, internal gains varied using PHPP (v9).
E. Compute the temperature normalisation factor (f_{ti}) for each *post hoc* model variant created in Step D (n_{PHPP} = 20 x 10 x 4 = 800).
F. Compare the standard deviation (SD) and the standard error of the mean (SEM) for the computed f_{ti}s in Step D. The SD assesses the spread of the computed f_{ti}s and the SEM indicates how well the computed means estimate the population mean. The smaller the SD, the more robust the f_{ti} and the smaller the SEM the greater the confidence that mean f_{ti} is representative of the population [46].
G. Repeat steps B to E using a standard SAP (2012) worksheet, creating n_{SAP} = 800.

For Step A, we obtained data from 20 Passivhaus homes located in the UK (for dwelling types see Appendix 2). The quality thresholds for inclusion in this set were:

- All dwellings to be certified Passivhaus
- Data be available on space heating and internal temperature
- If site specific weather data is unavailable, a suitable local weather station must exist.
- Data available for at least 12 months.

For Step B, 10 PHPP models were created using data from 5 domestic and 5 non-domestic buildings, whose data is summarized in Table 4. All the PHPP building models met the Passivhaus standard in terms of U-values, air tightness etc but each building model had a different specification. This provided sufficient means for testing a variety of realistic sizes and shapes, since these data are sourced from real buildings.

Domestic Building Type	**TFA**	**Non-Domestic Building Type**	**TFA**

Single dwelling A	120m^2	Community Centre A	430m^2
Single dwelling B	300m^2	Community Centre B	665m^2
Single dwelling C	600m^2	Education building	300m^2
Block of 22 apartments	1420m^2	University building	2800 m^2
Row of 4 town houses	350m^2	Office	550m^2

Table 4. Summary of domestic and non-domestic building types PHPP.

All the PHPP assessments were undertaken in earlier versions of PHPP (v9), as these were readily available. All the 20 dwellings from which post occupancy data had been collected had a TFA of less 300m^2. However, under the new assessment method for internal heat gains in PHPP (v9) these dwellings would have been assigned higher internal gains than the constant of 2.1Wm^{-2} used in earlier versions of PHPP. Hence, Cases 2 and 4 test the effect of using the PHPP (v9) values. This is summarized, together with the impact of default and localised solar gains and the corresponding SAP options, in Table 5. Note that internal gains default is different in SAP (variable) and PHPP (fixed, prior to v9).

		Internal gains data	
		Fixed (2.1 Wm^2)	**Variable (PHPP v9 *or* SAP (2012))**
Solar radiation data source	PHPP “Climate sheet regional data” *or* SAP (2012) climate data table U3	Case 1	Case 2
	Real data from CEDA	Case 3	Case 4

Table 5. Summary of four Cases: Case 1 uses the PHPP/SAP (2012) default setting for solar gain and fixed internal gains. Case 2 replaces fixed internal gains with varied internal gains based on floor area. Case 3 replaces PHPP/SAP solar radiation data with geo-temporally correct observed solar radiation data from the Centre for Environmental Data Analysis (CEDA) [47] and uses fixed internal gains. Case 4 uses internal heat gain settings depending on treated floor area and solar radiation data from CEDA (as Case 2).

The following method was applied for each of the four Cases in PHPP:

1) The PHPP climate sheet was changed to reflect the location and altitude for the specific site where post occupancy data was collected.
2) To calculate $Q\ Heating_{20}$The average monthly external temperature for each year of the monitoring was inputted in the PHPP ‘climate’ sheet. The internal temperature was set at the standard PHPP certification level of 20ºC. The space heating demand for each month from the ‘Heating’ Sheet was extracted and summed for the year. This gives the annual space heating demand for $Q\ Heating_{20}$.

3) To calculate $Q\ Heating_{real.}$ The average monthly external temperature from monitored data was inputted in the PHPP 'climate' sheet. For the same months, the average monthly measured internal temperature was inputted into the PHPP 'verification' sheet.' The subsequent monthly heating demand was taken from the 'heating' sheet and summed to give the annual space heating demand. This gives the annual space heating demand $Q\ Heating_{real}$.

The normalisation factor was then calculated as $f_{ti} = \frac{QHeating_{20}}{QHeating_{real}}$

The method described above was then replicated using SAP (2012) worksheets. Internal and external temperature data from the 20 dwellings was inputted into 10 different SAP (2012) worksheets. To allow comparison with $Q\ Heating_{20}$, the internal temperature of the living room was set to 20°C (as opposed to 21°C default in SAP (2012)). To test the robustness of the method, the SAP (2012) assessments from different dwelling types with varying floor areas were selected. The building fabric of these dwellings included Passivhaus and low energy homes, in addition some less efficient dwellings were included to test the robustness of the method. As SAP is for domestic dwellings, there were no non-domestic examples in the sample. Table 6 gives a summary of the dwelling types.

Domestic Building Type	**Gross internal floor area**	**Domestic Building Type**	**Gross internal floor area**
5 bed detached house	228 m^2	2 bed house	79 m^2
4 bed detached house	123 m^2	1 bed flat	42 m^2
4 bed detached house	300 m^2	2 bed flat	72 m^2
3 bed detached house	205 m^2	3 bed flat	95 m^2
3 bed town house	110 m^2	1 bed flat conversion	49 m^2

Table 6. Summary of domestic building types for SAP (2012).

3. Results

3.1. Calculation of normalisation factors in PHPP (v9) and SAP (2012)

Figure 2 is a box and whisker plot of the raw normalisation factors calculated from the measured internal and external temperature data from the 20 dwellings, for each of the 4 Cases in PHPP and SAP (2012). The results show that for 16 out of the 20 dwellings, there is a narrow range of variation between the normalisation factors calculated. However, for dwellings 1, 4, 16 and 17, the range of f_{ti} is much wider with the greatest range in Case 2 and 4 PHPP. SAP (2012) calculated a narrower range of normalisation factors across these four cases compared to PHPP. For all other dwellings, there was very little difference between the normalisation factors calculated in PHPP and those made in SAP (2012). To simplify further reading, we collectively term dwellings 1, 4, 16 and 17 as Dwelling Outliers (DO).

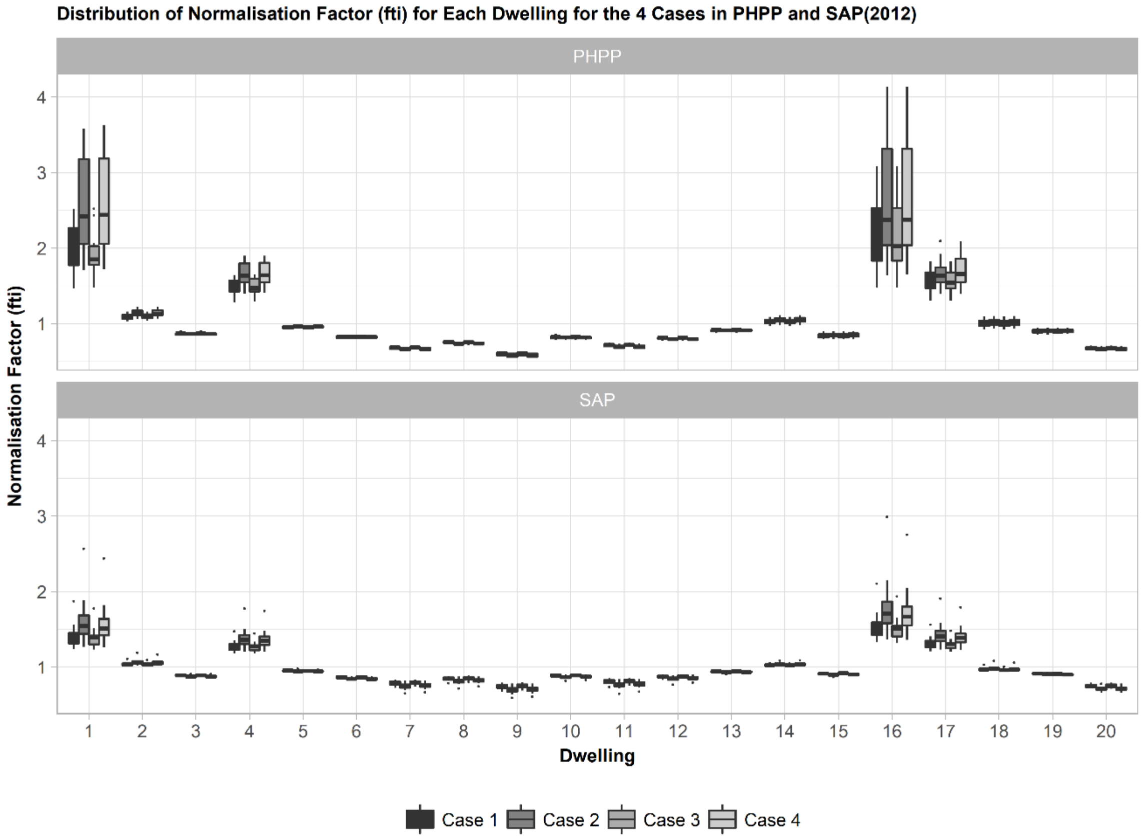

Figure 2 Distribution of the 10 calculated normalisation factors for each dwelling for each Case (PHPP) and SAP (2012) (see Table 6 for the definition of each Case). In each plot, the bar shows the mean, and the box the inter-quartile range.

Variation is further demonstrated by the standard deviation (SD) and the standard error of the mean (SEM) of the normalisation factors. Figure 3 shows all 4 Cases tested in PHPP and SAP (2012). We find that SD(f_{ti}) < 0.06 for non-DO dwellings and >0.07 SD(f_{ti}) < 0.82 for DO dwellings. The widest range of variation is found within Cases 2 and 4 where varied internal gains were modelled. This variation in SD is greater in PHPP than SAP (2012).

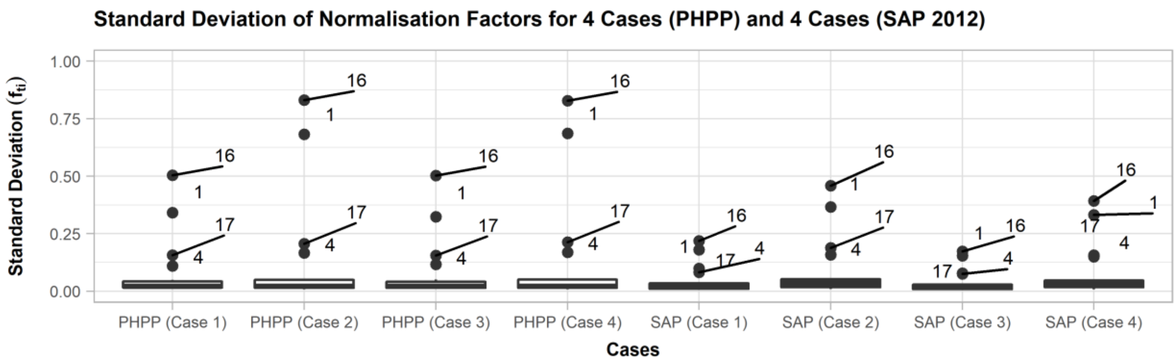

Figure 3 Box and whisker plot of the SD of the 10 normalisation factors (f_{ti}) for the 4 Cases (PHPP) and SAP (2012) with outliers labelled

The DOs are the same four dwellings as identified in Figure 2. For all non-DO PHPP and SAP (2012) Cases, the variation in SEM of f_{ti} is very small (SEM<0.02) as shown in Figure 4. For the DOs, in each Case, SEM ranges from 0.03 to 0.26. Again, the largest range of variation between SEM is found within Cases 2 and 4, in both assessments, where varied internal gains were modelled.

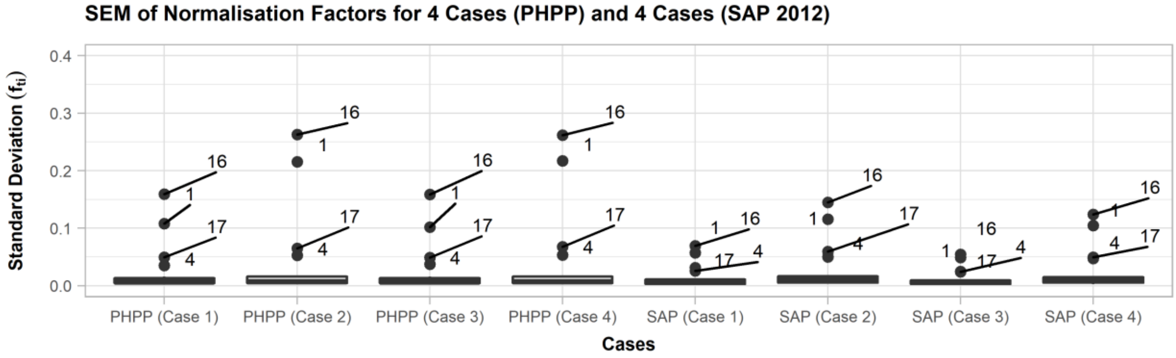

Figure 4 Box and whisker of the SEM of the 10 normalisation factors (f_{ti}) for the 4 Cases (PHPP) and SAP (2012) with outliers labelled.

3.2. Impact on space heating demand

The 10 normalisation factors (f_{ti}) calculated for each of the 4 Cases (PHPP) and SAP (2012) were applied to the measured annual space heating demand (normalised by TFA) from the 20 dwellings. Outliers were included in the calculation of f_{ti} for each case.

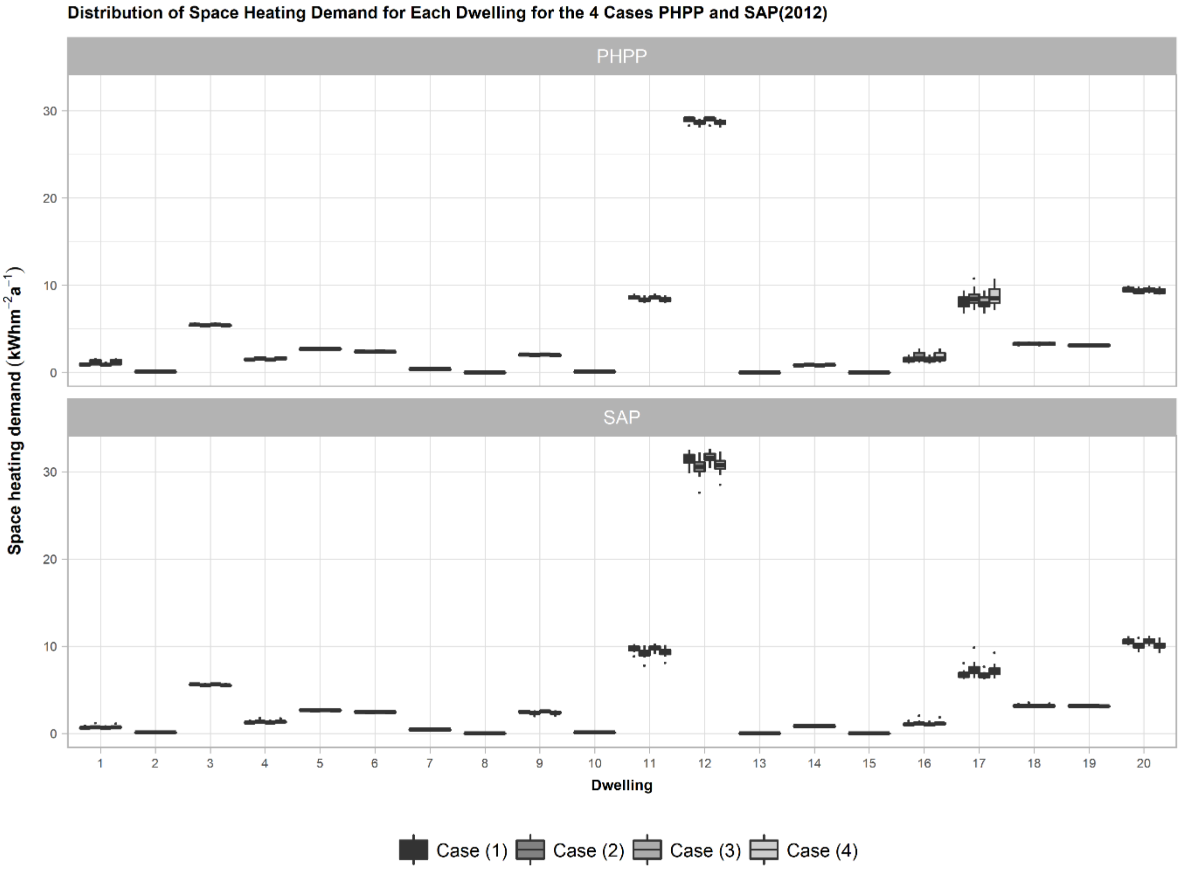

Figure 5. Range of normalised space heating demand ($kWha^{-1}$) for the 4 Cases in PHPP and SAP (2012).

Figure 5 shows that 10 dwellings had little or no space heating demand (< 1kWh.m^{-2}. a^{-1}). Therefore, for these dwellings, the impact of applying the normalisation factors will be limited. Dwellings 11, 12, 16, 17 and 20, which are primarily characterised by higher space heating demand, showed a wider variation in normalised demand once f_{ti} had been applied. However, even within this group the difference between normalised space heating demand for the 20 dwellings is not large, ranging from 0.5 to 4.9 $kWh.m^{-2}a^{-1}$. Differences can also be seen between the PHPP and SAP assessments and these are further analysed below.

The impact of applying the 10 f_{ti}s to space heating demand is demonstrated by the SD of normalised space heating demand for the 4 Cases (PHPP) and SAP (2012) shown in Figure 6 below.

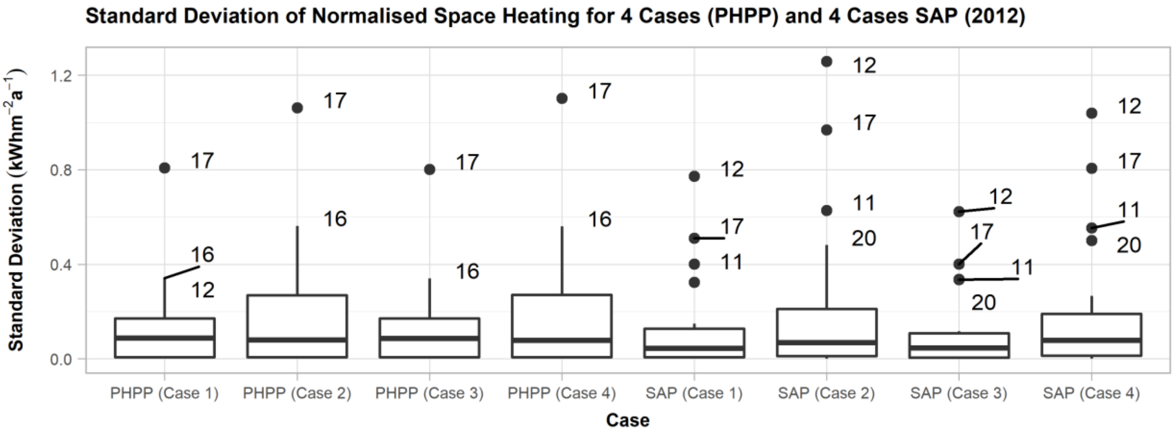

Figure 6. SD of normalised space heating demand for each of the 4 Cases (PHPP) and SAP (2012) with outliers labelled.

The results in Figure 6 show that the distribution of SD of the measured annual space heating demand, when the normalisation factors are applied, for the 4 Cases in PHPP and SAP is very consistent. For Cases 1 and 3, SD is less than 0.9 $kWh.m^{-2}$. a^{-1}, and for Cases 2 and 4, the SD is less than 1.3 $kWh.m^{-2}$. a^{-1}. Unsurprisingly, outliers are dwellings with the highest annual space heating demand (see Figure 5). Though DOs are contained in the outliers, non-DO dwellings also appear (e.g. 11, 12, 20), suggesting that space heating demand has a bigger impact on the SDs than f_{ti}. This is supported by the SEM data (Figure 7), which is less than 0.1 for most cases, and the outliers following the same pattern as in Figure 6.

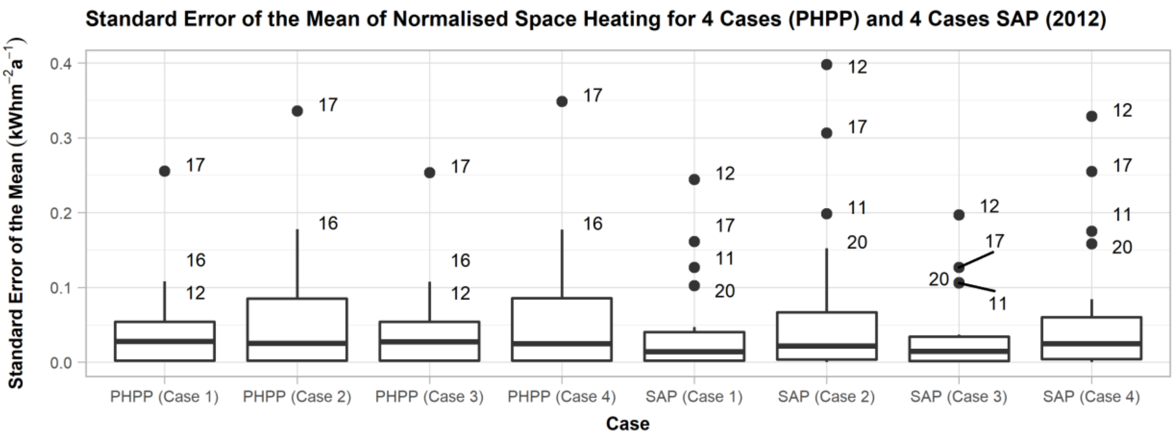

Figure 7. SEM of normalised space heating demand for each of the 4 Cases (PHPP) and SAP (2012) with outliers labelled.

3.3.Impact of variables

Here we undertake further analysis of individual variables to understand why the range of f_{ti} is significantly higher in DOs (see Figures 2 and 5) compared to the rest of the dwellings modelled. Since there are only three variables (t_i, IHG, solar) that were manipulated in the modelling, we consider each of these in turn.

Internal temperatures

Within the 20 dwellings, there were variations in average winter internal temperatures. Figure 8 below shows the mean internal temperature during the heating season (October to May) for each dwelling compared to the internal temperature assumed in the PHPP and SAP (2012) assessments (20ºC). 16 of the 20 homes had an internal temperature either the same or above the modelling assumption in PHPP and SAP (2012). DOs had an average internal winter temperature below the assumption in PHPP and SAP (2012) and these homes correspond to the dwellings with the greater range of calculated normalisation factors.

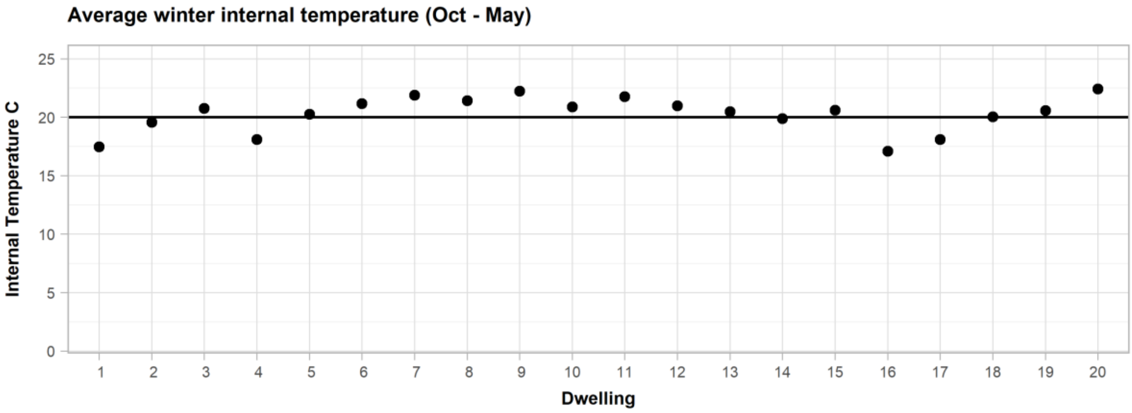

Figure 8. Average measured internal winter temperature (October to May) for each dwelling (circles) compared to the assumed internal temperature of 20ºC (solid line) used in the PHPP and SAP (2012) models.

Average winter internal temperature was plotted against the SD of the f_{ti} for all four cases in PHPP and SAP (2012) (Figure 9, Figure 10).

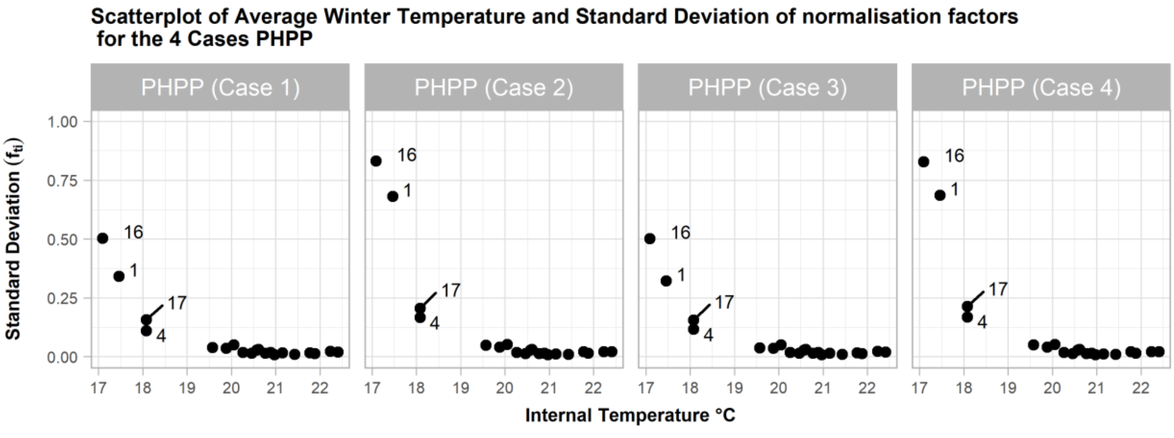

Figure 9. Standard deviation of the 10 normalisation factors (f_{ti}) with measured internal winter temperature for the 4 Cases (PHPP)

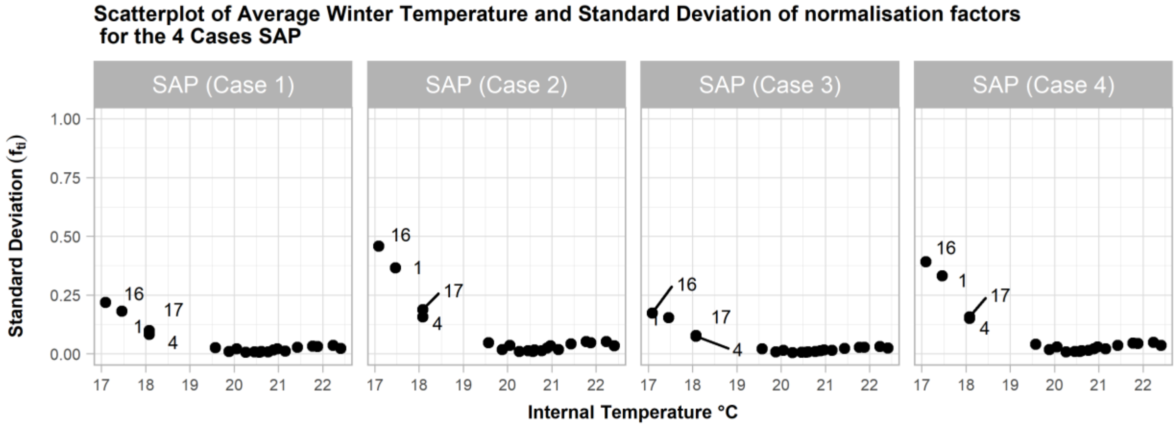

Figure 10. Standard deviation of the 10 normalisation factors (f_{ti}) with measured internal winter temperature for the 4 Cases SAP (2012).

Figure 9 and Figure 10 suggests that internal temperature has an influence on f_{ti}. Dwellings 1, 4, 16 and 17 had an average winter internal temperature ≤ 18.1ºC and the highest ranges of f_{ti}. This is shown by the increased SD of between 0.1 and 0.81. The lower the measured internal temperature, the higher the range of f_{ti}. Once internal temperatures were close to the modelling assumptions of 20°C, the SD of f_{ti} is below 0.05. When the measured internal temperature rose above the assumption of 20ºC, the range of f_{ti} also remained within this lower range. Therefore, higher internal temperature does not have the same effect on f_{ti} as lower temperatures. This pattern was consistent across all four cases calculated in PHPP and SAP. There is a slightly larger range of normalisation factors in Case 2 and 4, where internal gains were varied, and this is studied next.

Internal gains

The impact of varied internal gains on the range of normalisation factors (f_{ti}) was considered for Cases 2 and 4 only. The internal gains assumptions were varied to reflect the different TFA according to the methods used in both PHPP (v9) and SAP (2012). Note that there are higher IHG assumptions in the SAP (2012) assessment.

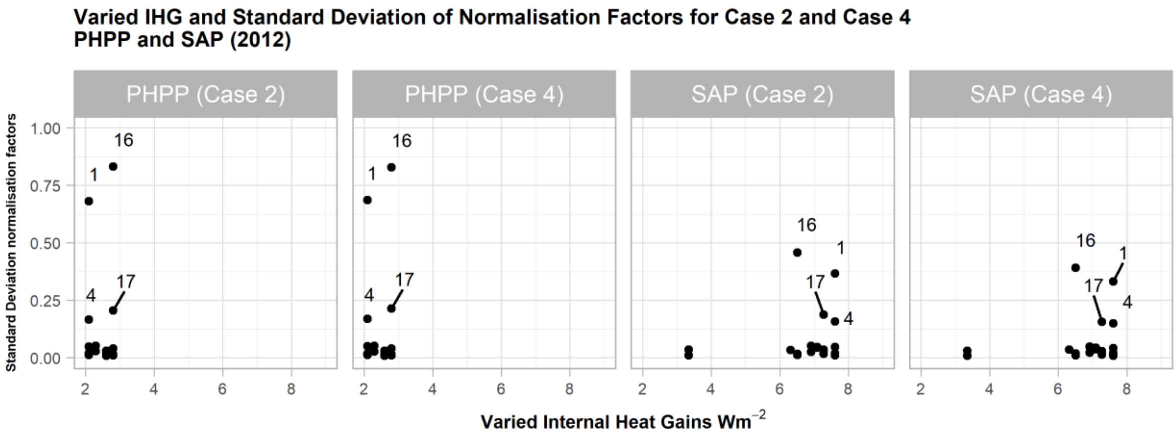

Figure 11. Standard deviation of normalisation factors (f_{ti}) with internal heat gains Cases 2 and 4 only. The number indicates the dwelling ID for each DO.

Figure 11 shows the SD of f_{ti} plotted against the varied internal gains (Wm^{-2}), for Case 2 and Case 4 only. Since DOs have both low and high internal heat gain assumptions in the PHPP (v9) and SAP (2012) assessments, we can conclude that variation in IHG is not influencing the calculation of f_{ti}.

Solar gains

Figure 12 below shows the SD of normalisation factors (f_{ti}) against annual solar radiation, in Cases 3 and 4 where CEDA irradiation readings were substituted for the climate data in PHPP and SAP (2012). The 4 dwellings with the greatest SD are labelled and are all DOs. Since the DOs have both higher and lower measured annual solar radiation, we conclude that solar radiation levels are not influencing the calculation of f_{ti}.

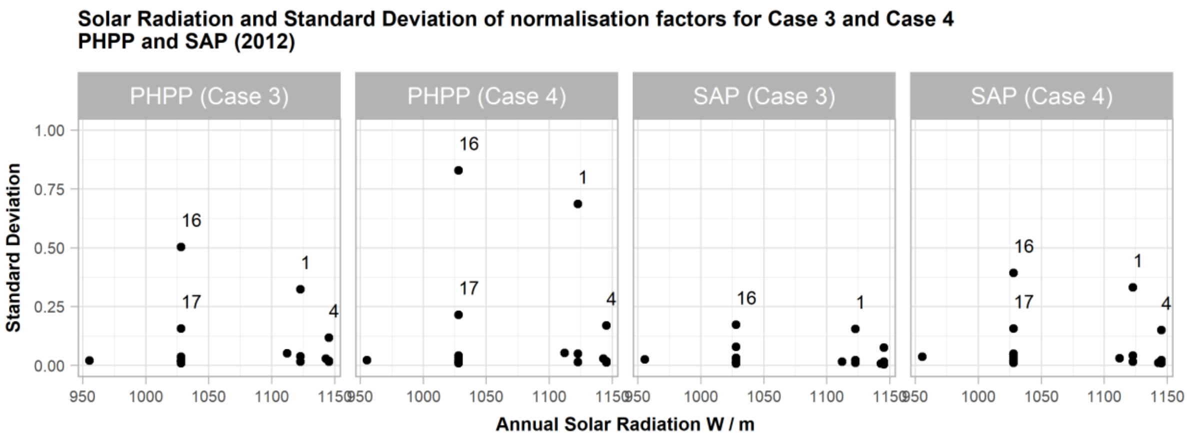

Figure 12. Measured annual solar radiation and SD of correction factors Case 3 and Case 4 PHPP and SAP (2012). The number indicates the dwelling ID for each DO.

Dwelling type

Table 9 lists the dwelling types from which the measured data were taken and demonstrates that there is no relationship between the DO's and a particular type of dwelling.

4. Conclusion

Normalising measured space heating energy data enables in-use data to be compared more accurately to building models, by considering the effect of varied internal and external temperatures on space heat demand. Both PHPP and SAP (2012) allow for modifications to be made to the model using locally collected data. Predicted space heating demand can be modified by inputting measured monthly average internal and external temperatures into the PHPP and SAP (2012) assessment sheets. This generates a more accurate heating degree hour calculation for each month which improves annual degree day data, as suggested in CIBSE TM 41. Being able to adjust for these differences between real and modelling temperature assumptions means these factors to be excluded from any performance gap analysis.

When undertaking post occupancy monitoring, the site specific PHPP or SAP assessment may not be available. This means that without an alternative method it would not be possible to undertake normalisation for internal and external temperatures on the measured space heating demand. The results showed that a calculation of a normalisation factor (f_{ti}) can be undertaken without the site specific PHPP or SAP sheets and that a building with a different form and function can used, as both domestic and non-domestic PHPP assessment sheets were tested. A wide range of buildings types with varying energy efficiency were used in the SAP testing.

For all 4 Cases (PHPP) and SAP (2012), 80% of the calculated normalisation factors had an SD of <0.05 and 80% had a SEM of < 0.02. To investigate why the remaining 20% of dwellings displayed a higher SD and SEM, which were consistent across all four Cases (PHPP) and SAP (2012), we compared them against the three manipulated variables: internal temperature, internal heat gains and local solar radiation data. Analysis demonstrated that there was a clear relationship between variation in the normalisation factors calculated and lower winter internal temperatures. When the average measured internal temperatures were below 20ºC, the temperatures assumed in the PHPP and SAP (2012) calculations, the variation in the normalisation factors calculated increased. This variation was greater in the PHPP assessments compared to SAP (2012) and suggests that the space heating demand calculation may be more sensitive to low internal temperatures, as other factors such as internal and solar gains will make up a greater proportion of overall heat gains. However, normalisation factors were not observed to be influenced by either variable internal heat gains nor the use of local solar radiation data. We hence conclude that low internal temperatures exert the greatest influence on the reliability of the normalisation factor calculation.

However, when the normalisation factors are applied to measured space heating demand – which is the variable of interest – the computed variation in t_{fi} has a demonstrably smaller impact. This is shown in additional DOs appearing in the SAP (2012) Cases, when actual space heating demand has a greater influence on variation rather than the calculated normalisation factors themselves. For 90% of the dwellings the SD of normalised space heating demand was less than 1 kWh.m^{-2}a^{-1} and the greatest SD was 1.27 kWh.m^{-2}. a^{-1}. This translates to a maximum standard error of 0.4 kWh.m^{-2}a^{-1}. Given that the energy consumption for the cases with the greatest standard errors are typically less than 10 kWh.m^{-2}a^{-1} (i.e. an overall error of 4%), we conclude that temperature normalisation using a *post hoc* model is appropriate.

The research in this paper has a practical application for dwellings assessed to the Passivhaus standard as the normalisation factor (f_{ti}) can be calculated using a non-site specific PHPP assessment. Buildings assessed using the SAP methodology can also be normalised and again the site-specific sheet is not needed. From the data collected, when measured internal temperatures are close to or above the modelling assumptions then either a PHPP or a SAP (2012) sheet could be used for normalisation as the results were consistent across the two tools.

5. Acknowledgements

WARM low energy practice Plymouth provided post occupancy data, Kym Mead assisted in providing PHPP models and Setareh Mollajafari assisted in the initial SAP modelling

6. Funding

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7. List of figures

Appendix 1 Definition of terms

Term	Units
Heat transfer co-efficient	$W/m^{-1}K$
Internal heat gains	Wm^{-2}
Solar radiation	W/m
Space heating demand	$kWhm^{-2}a^{-1}$
Temperature	°C

Table 7. Terms and units.

Appendix 2 Dwelling types with measured data

Table 8:List of dwelling numbers against types. DOs are indicated with a *.

Dwelling Type	Dwelling No.

2 bed end terrace	1*
	4*
	3
	6
2 bed mid terrace	2
	5
3 bed end terrace	7
	9
	10
	11
	13
	14
	16*
	18
3 bed mid terrace	8
	12
	15
	17*
Detached bungalow	19
Detached house	20

Table 8.

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